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Airborne Studies of the Emissions from the Volcanic Eruptions of Mount St. Helens

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Abstract. *The concentrations of particles less than 10 micrometers in diameter in the ash emissions from Mount St. Helens have been more than 1000 times greater than those in the ambient air. Mass loadings of particles less than 2 micrometers in diameter were generally several hundred micrograms per cubic meter. In the ash clouds, produced by the large eruption on 18 May 1980, the concentrations of several trace gases generally were low. In other emissions, significant, but variable, concentrations of sulfur gases were measured. The 18 May eruption produced nuées ardentes, lightning flashes, and volcanic hail.*

Mount St. Helens, which is situated about 140 km south of Seattle in the Cascade Mountains of Washington State, ended its 123 years of dormancy on 20 March 1980 with a single small earthquake registering 4.1 on the Richter scale (*1*). Seismic activity increased steadily, becoming nearly continuous by 25 March.

The first eruption, which occurred at 2036 Universal Time (*2*) on 27 March 1980, ejected volcanic material to an altitude of 4.9 km (*3*). Airborne measurements and observations made from the University of Washington's research aircraft (*4*) began on 28 March when periodic (about every 5 to 10 minutes) eruptions of ash, and more frequent but shorter duration emissions of steam, reached up to 6.1 km (Fig. 1A). The size spectra of particles were measured in a cloud of ash 13 km downwind of the mountain (Fig. 2A). The number concentrations of particles with diameters between 1 and 10 μm in this cloud were up to 1000 times greater than in the ambient air, but particles < 1 μm in diameter were found in concentrations similar to those in the ambient air. The mass concentrations of particles < 2 μm in diameter in the ash cloud and in the ambient air were about 600 and 30 $\mu g\ m^{-3}$, respectively. Gaseous sulfur, almost entirely reduced sulfur, which we presume by its smell to be H_2S, was detected in concentrations of up to 240 ppb (*5*).

Between 28 March and 17 May, when the volcanic activity was quite variable, seven flights were made. The measurements on 2, 4, 8, and 11 April showed concentrations of total gaseous sulfur ranging from 15 to 38 ppb with quite variable contributions from H_2S and SO_2. However, on 8 May the total gaseous sulfur concentrations had returned to values similar to those measured on 28 March.

Early on 18 May, seismic activity

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and visible emissions had virtually ceased when suddenly a major eruption occurred at 1532. A large portion of the north face of the mountain collapsed in avalanches and pyroclastic flows, devastating a wide area north and east of the mountain; this eruption caused the first recorded human deaths due to volcanic activity in the continental United States. The explosive eruption ejected material to an altitude of about 20 km, and ash was carried eastward over Washington, Idaho, and Montana within a few hours.

We started our airborne measurements in the vicinity of Mount St. Helens at ~ 1900 on 18 May. Violent emissions of ash were still continuing at this time (Fig. 1B), numerous nuées ardentes (glowing avalanches) were cascading down the sides of the mountain, and lightning flashes, presumably caused by charge separation during particle collisions in the very dense clouds of ash, were common. We attempted to obtain our first measurements at ~ 2000 at the edge of the dark ash plume ~ 37 km downwind and east of the volcano but were driven back as the aircraft was bombarded with clumps of loosely aggregated material (up to fist size) that disintegrated on hitting the plane; similar bombs, both dry and wet, were observed on the ground 12 km from the summit of Mount St. Helens within a few minutes of the eruption (*6*). We believe these bombs were formed by the rapid aggregation of ash particles in the plume; we propose they be termed volcanic hail (*7*).

We obtained measurements of particle size distribution at the periphery of the ash plume, ~ 9.3 km downwind at ~ 2010 (Fig. 2B). For particles 0.01 to 10 μm in diameter, the concentrations in the plume varied from a factor of 4 to over 1000 times those in the ambient air. For particles < 2 μm in diameter, the mass loading in the plume was ~ 95 $\mu g\ m^{-3}$ compared to $< 0.1\ \mu g\ m^{-3}$ in the ambient air. Optical polarization and x-ray diffraction measurements showed that the particles consisted primarily of lithic rock fragments, largely plagioclases, with some apparently juvenile glasses.

The concentrations of sulfur gases measured at the periphery of the main ash cloud on 18 May were generally only slightly greater than those found in the ambient air; nitrogen oxides and ozone remained at or below ambient concentrations. It is possible that the small quantity of sulfur gas reflects absorption of reactive trace gases on the ash plume's very large total particle surface area. However, the ash samples we have analyzed showed generally small amounts of soluble materials such as sulfate, while samples from the stratosphere collected on U-2 flights showed the main cloud to steadily increase in acidity over a period of days, evidently indicating the presence of significant trace gas concentrations (*8*). Thus these observations may reflect temporal or even altitude variations.

In addition to the dark ash plume, smaller whitish-looking clouds of effluents were observed on 18 and 19 May along the edges of the main plume (Fig. 1C) (*9*). These clouds were small enough to be penetrated completely by our aircraft. Particle size distribution measured near the center of such a cloud (Fig. 2C) showed that for particles < 0.1 μm in diameter, the concentrations were similar to those in the ambient air, but the concentrations of particles from ~ 0.1 to 30 μm in diameter were up to 100 times greater than in the ambient air. The mass concentrations of particles < 2 μm in diameter in the whitish clouds and in the ambient air were ~ 30 and 5 $\mu g\ m^{-3}$, respectively. The concentration of total sulfur gases in these clouds, primarily SO_2, was at least 13 ppb, compared to ~ 6 ppb in the ambient air. Nitrogen oxides and ozone concentrations in the whitish clouds were similar to those in the ambient air.

Our final measurements on this flight were taken near the top of the main ash plume (~ 5.2 km downwind) late in the evening, when the volcanic activity was much less than earlier in the day. These measurements showed a high concentration of total sulfur gases (~ 1 ppm) that consisted primarily of H_2S.

The emissions of particles and gases from the volcano measured on our next flight, much later on 19 May, were considerably lower than on the previous flight, although they were still considerable. Particle size spectra were measured on the periphery of the main ash emissions (Fig. 2D), H_2S concentrations

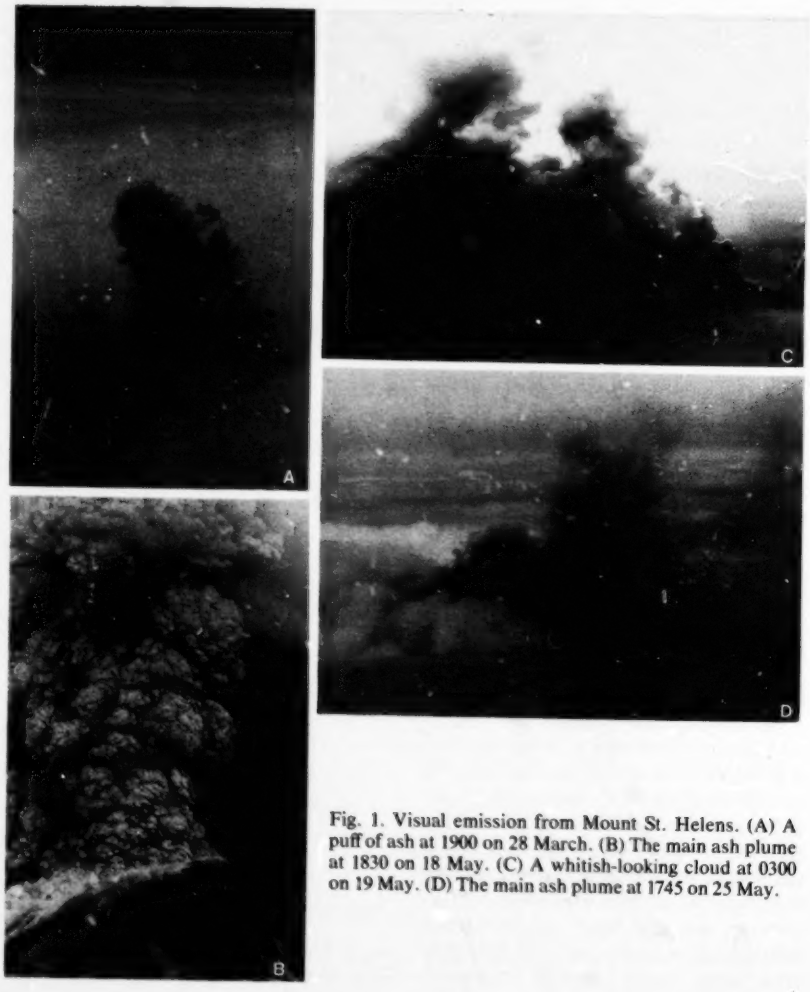

Fig. 1. Visual emission from Mount St. Helens. (A) A puff of ash at 1900 on 28 March. (B) The main ash plume at 1830 on 18 May. (C) A whitish-looking cloud at 0300 on 19 May. (D) The main ash plume at 1745 on 25 May.

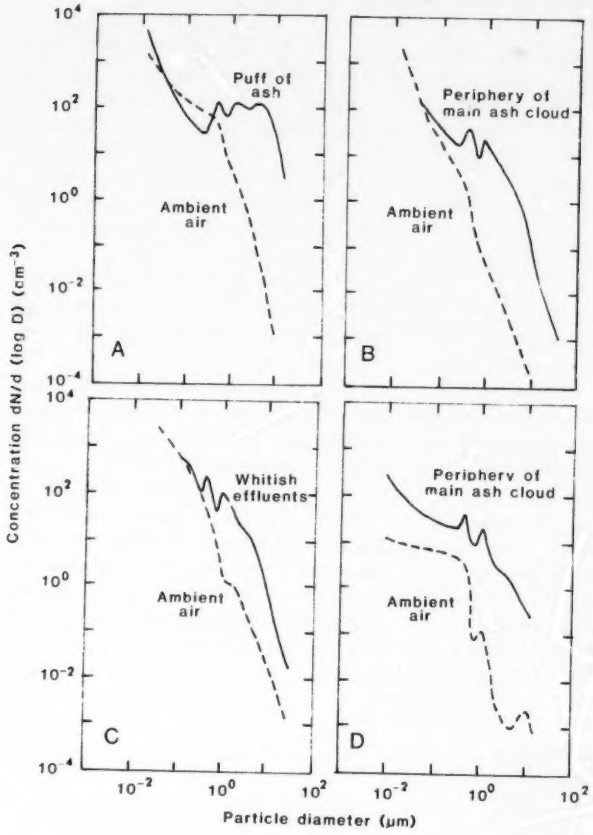

Fig. 2. Size spectra of small particles: (A) in a puff of ash at an altitude of 3 km and 13 km downwind of the volcano at 2239 on 28 March; (B) at the periphery of the dark ash cloud at an altitude of 3 km and 9.3 km downwind of the volcano at 2010 on 18 May; (C) near the middle of the whitish-looking clouds at an altitude of 3.2 km and 130 km downwind of the volcano at 0230 on 19 May; (D) at the periphery of the main ash cloud at an altitude of 2.7 km and 22 km downwind of the volcano at 2140 on 19 May.

were high (~ 0.5 ppm), but SO_2 concentrations were near ambient values.

Mount St. Helens exploded violently for the second time at 0932 on 25 May when ash was ejected to an altitude of 13.7 km (Fig. 1D). Particle size measurements obtained in the periphery of the main ash plume just after 1800 were similar to those obtained on 18 May. Unlike the 18 May measurements, we detected consistently high amounts of total sulfur gases, up to 110 ppb, with 13 to 95 ppb of H_2S and 3 to 6 ppb of inert sulfur-containing gases.

Measurements on 30 May and 4 June showed continuing gaseous emissions but much reduced ash emissions. A significant fraction of the smaller particles on these 2 days consisted of soluble material, with quantities of SO_4^-, Br^-, F^-, and Cl^-.

After the 25 May eruption both the total sulfur gas emissions and the SO_2 fraction increased dramatically, and after the violent eruption of 13 June most of the sulfur gas was SO_2. Associated with the increase in SO_2 was an increase in the particulate sulfate, as would be expected both from the precursor-product relation between SO_2 and SO_4^{2-} and the possibilities of direct injection of H_2SO_4. Soluble sulfate fluxes of about 25 g sec^{-1} were measured on both 4 and 18 June. During this period a significant fraction of the aerosol contained spherical fume particles and haloed particles that appear to have been impure H_2SO_4 droplets similar to those found at Augustine Volcano, Alaska, in January 1976 and April 1977 (*10*). On 18 June the hot outgassing plume generated a small cumulus cloud that capped the caldera. The cloud droplets were found to have a $pH \leq 1$.

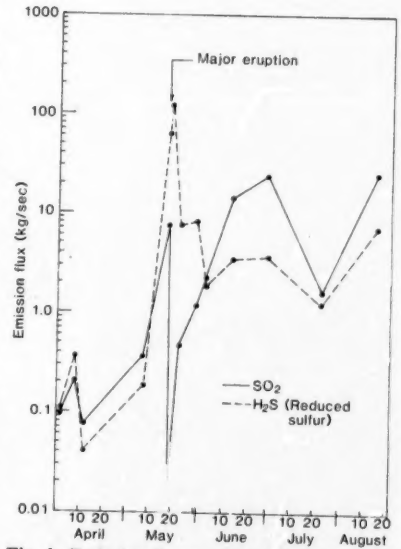

Fig. 3. Emission fluxes of SO_2 and H_2S measured from Mount St. Helens.

Elevated NO_2 concentrations were observed only on one occasion. On 13 June, after the third violent eruption sequence, concentrations approaching 400 ppb were observed at a range of 8 km, resulting in an estimated emission flux of 7 kg sec^{-1}.

The gaseous sulfur emissions summarized in Fig. 3 as total fluxes were deduced from multiple traverses of the plumes and simultaneous measurements of horizontal winds. The emission fluxes for 18 May, however, are based on more fragmentary data of plume volume and are, therefore, subject to large potential error. These fluxes are quite similar to those we measured from the Augustine Volcano during its eruptive phase in February 1976 (*9*).

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References and Notes

1. All seismic data in this report are taken from the logs of S. Malone at the Department of Geophysics, University of Washington, Seattle.
2. All times are Universal Time.
3. All heights are given above mean sea level.
4. P. V. Hobbs, D. A. Hegg, M. W. Eltgroth, and L. F. Radke have described the research instrumentation aboard this aircraft [*Atmos. Environ.* **13**, 935 (1979)].
5. Measurements of gaseous sulfur were made with a flame photometric detector with scrubbers which remove sequentially from the total sulfur stream the reduced sulfur species and then both reduced and oxidized species, allowing separation of oxidized sulfur (presumed SO_2), reduced sulfur (presumed on the basis of smell to be H_2S), and the comparatively inert species such as carbonyl sulfide and CS_2.
6. K. Rohnholm, personal communication.
7. Vulcanologists have referred to similar bombs as accretionary lapilli. These are most commonly observed to be less than 1 cm in diameter but have been observed as large as 15 cm during the 1902 eruptions of Mont Pelée. However, given the apparent similarities to hail formation, we consider volcanic hail to be a far more descriptive term.
8. J. A. Ogren, R. T. Charlson, L. F. Radke, S. K. Domonkos, *Science* **211**, 834 (1981); *NASA/FAA Bull. Upper Atmos. Programs Issue 80-3* (1980).
9. We also distinguished between ash (brown clouds) and white emissions in our airborne studies of the St. Augustine Volcano eruption [P. V. Hobbs, L. F. Radke, J. L. Stith, *Science* **195**, 871 (1977); see Hobbs *et al.* in (*10*); J. L. Stith, P. V. Hobbs, L. F. Radke, *J. Geophys. Res.* **83**, 4009 (1978)].
10. R. D. Cadle and E. J. Mroz, *Science* **199**, 455 (1978); P. V. Hobbs, L. F. Radke, J. L. Stith, *ibid.*, p. 457.
11. We thank all members of our airborne crew for their help in obtaining these measurements. We are grateful to T. Irving for optical and x-ray analyses of ash samples. Our measurements were made possible by prompt actions on funding by B. Fogle, G. Bierly, R. Dirks, and D. Senich of the National Science Foundation (grant DPP 79-20857), and by W. Wilson of the Environmental Protection Agency (grant R005263-02). Contribution 562, Atmospheric Sciences Department, University of Washington.

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